Pipeline Optimization Program (PLOP)

by Derek Wilson

PURPOSE: This technical note describes the Pipeline Optimization Program (PLOP), a computer program that optimizes pipeline transport of slurry based on slurry pump performance, material characteristics, pipeline characteristics, and industrial standards. PLOP uses a rules-based programming language, C Language Integrated Production System (CLIPS). Rules-based languages are advantageous in addressing decision-making problems inherent to slurry pump and pipeline transport and are also consistent with the framework of the Dredging Operations Decision Support System (DODSS, *https://dodss.wes.army.mil/wiki/0*). PLOP compiles industry standards and governing physical principles into a single executable file that makes decisions and processes output based solely on the initial input parameters.

BACKGROUND: The decision-making process associated with pipeline slurry transport is vast and tedious. Simplifying this process with computer applications involves incorporating expert and heuristic knowledge into the application source code. CLIPS readily performs such operations as well as conventional numerical procedures. CLIPS is an open source expert systems program available at *http://www.ghg.net/clips/CLIPS.html*. CLIPS has been used in developing the PLOP program at the U.S. Army Research and Development Center (ERDC).

CLIPS: C Language Integrated Production System (CLIPS) is a rules-based programming language. Rules-based languages input data as facts. Facts that correspond to certain conditions execute rules. These rules process the facts to produce output. Rules may be regarded as conditional elements found in procedural languages. However, there is no strict hierarchy or order in which these rules execute. Rules are executed whenever facts that meet the conditional elements are asserted. Because of this principle, CLIPS holds the advantage over procedural language for pattern matching. CLIPS does not need to iterate through all input data to determine a match. Rather, rules that specify matching conditions determine which input corresponds to these conditions and processes that input accordingly.

When expert or heuristic knowledge is heavily involved in a programming application, CLIPS' capability becomes readily apparent. Processing expert or heuristic knowledge is essentially pattern and criteria matching. Matching operations that span a vast amount of data would be unwieldy for procedural languages.

CUTPRO ANALOGIES: CUTPRO was developed by Stephen Scott (1998, 2000) as a tool to monitor and predict cutterhead dredge efficiency. CUTPRO was written in FORTRAN procedural language. CUTPRO uses the principles governing solid transport with centrifugal pumps developed by Wilson et al. (1997). CUTPRO calculates the pump requirements given pipeline and material characteristics and the rate of transport. PLOP, however, determines the production rate of slurry transport given the pump hydraulic characteristics considered for the

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operation as well as the pipeline and material characteristics. PLOP, therefore, solves for CUTPRO in reverse.

PROGRAM METHODS:

Input Format. The input data are stored as facts for CLIPS to process. Input data are divided into three categories: industrial standards data, pump characteristics data, and pipeline system and materials data. The industrial standards data, it is assumed, are relatively universal and are not subject to change. Pump characteristics data, although variable, are not considered subject to change within any given execution of the program. Pipeline and materials data are subject to the most change, since they will define the overall performance of the slurry transport application. This is what the user is expected to concentrate on when optimizing the pipeline system.

The pipeline and material facts are input as the following variables:

- Elevation difference (Δz): Difference in elevation from the pump to the discharge point [meters] Default value is 10 m (32.8 ft).

- Digging depth (Δz_d): Depth of the pipe intake [meters]. Default value is 3 m (9.8 ft).

- Pipeline length (L): Discharge length of the pipeline system [meters]. Default value is 2,000 m (6,560 ft).

- Pipeline diameter (D): Discharge diameter of the pipeline [meters]. Default value is 0.609 m (2 ft).

- Equivalent length (L_{eq}): Equivalent length of the pipeline superimposed on the pipeline system due to minor losses in the from the intake, elbows, and constrictions. Typical value is 40 pipeline diameters [meters]. Default value is 25 m (82 ft).

- Suction length (L_s): Length of pipeline from the intake to the pump [meters]. Default value is 10 m (32.8 ft).

- Suction diameter (D_s): Diameter of the pipeline along this length [meters]. Default value is 0.609 m (2 ft).

Figure 1 illustrates the relationships among these variables. The material data define the pertinent material characteristics as follows:

- d_{50}: Average particle size of dredged material [meters]. Default value is 0.25 mm.

- d_{85}: Particle diameter in which 85 percent of all particles are finer than [meters]. Default value is 0.5 mm.

- x_h: Mass fraction of silt and clay. Default value is 0.0.

- S_m: Maximum slurry relative density expected in the pipeline system. Default value is 1.32.
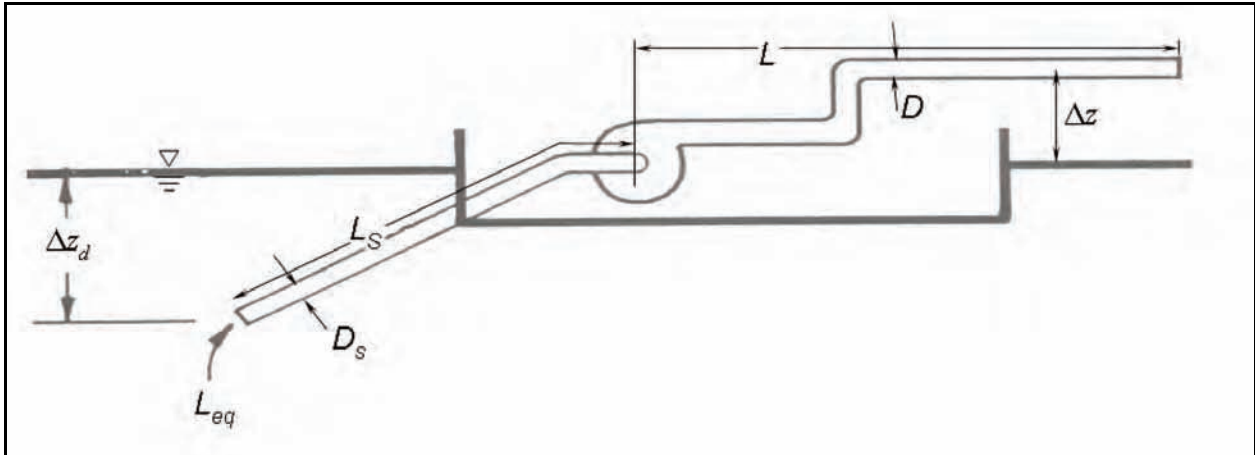
Figure 1.   Pipeline system geometry

If the system data or material data are asserted without specific values for these slots, the default values are automatically applied.

Pump characteristic data are stored as multiple pump-characteristic facts. These facts store the pump curve data as follows:

- Pump number: The pump identification name or number.

- Flow rate: Volumetric flow rate through the pump (m^3/s).

- Head: Dynamic head delivered by the pump at the corresponding flow rate (meters of slurry).

- NPSHR: Net Positive Suction Pressure Head required at pump intake to prevent cavitation (meters of slurry).

- RPM: Angular velocity of the pump impellor (RPM).

- Efficiency: Pump output efficiency (percent).

- Acceptability: Boolean expression stating whether or not the values for this pump performance point are practical for the pipeline and material characteristics specified.

Industrial standards data are obtained from Wilson et al. (1997) for their extensive research conducted with slurry pump design and implementation. These facts relate the minimum and maximum acceptable pump flow rates as a function of particle diameter, mixture density, and pump casing shell type. The data as published by Wilson et al. are used to determine the acceptability of the pump facts. The industrial standards data are formatted into the pump-op-limits and shell-type-limits fact templates as follows:

```
(deftemplate pump-op-limits (slot class)
                 (slot max-discharge-vel)
                 (slot max-suction-vel)
                 (slot max-impeller-prph-speed))
```

```
(deftemplate shell-type-limits-of-Qbep
                (slot class)
                (slot shell-type)
                (multislot min-max-percent-QBEP))
```

The parameters for these templates are described as follows:

- Class: Scale from 1 to 4 based on the slurry density and average particle size. A higher pump class value indicates more abrasive slurry. The pump class value relationship is illustrated in Figure 2.

- Max-discharge-velocity: Maximum slurry velocity through the discharge of the pump.

- Max-suction-velocity: Maximum allowable slurry velocity through the intake of the pump.
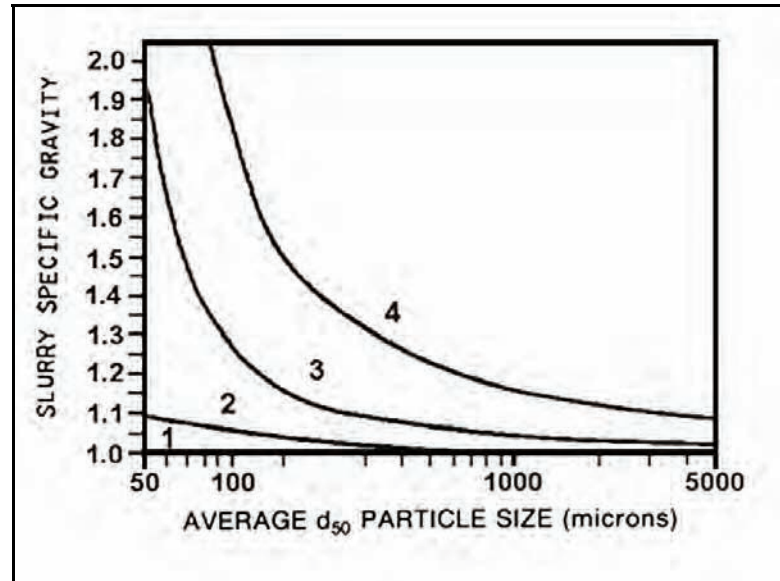
Figure 2.   Pump class as a function of d_{50} and S_m (from Wilson et al. (1977))

- Max-impeller-prph-speed: Maximum impellor tip speed; essentially the product of the RPM and pump diameter. A typical 0.8m impellor diameter is automatically assumed for simplicity.

- Shell-type: Characterizes the pump shell geometry as annular, volute, or semi-volute (see Figure 3). Semi-Volute is automatically the assumed shell type.
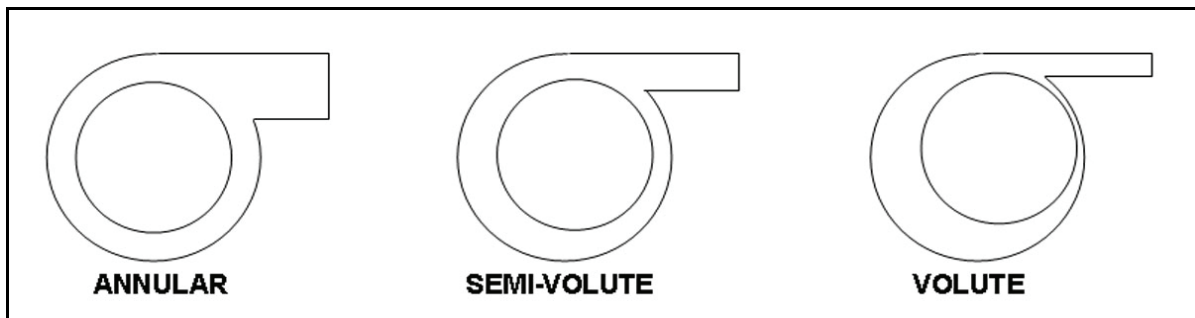
Figure 3.   Pump shell types adapted from Wilson et al. (1997)

- Min-max-percent-QBEP: Each pump has a flow rate that produces maximum pump efficiency (approximately 85 percent). This is referred to as the best efficiency point (BEP). In the interest of acceptable wear rate on the pump, industrial standards dictate that the flow

rate through the slurry pump cannot exceed or recede a specified percentage of the flow rate corresponding to the BEP.

Pump Acceptability Rules.   The facts for pump performance, industrial standards and pipeline and material characteristics are processed by pump acceptability rules to determine the industrial practicality range of each pump.   The pump performance facts acceptability slot is labeled as either yes (acceptable) or no (unacceptable). Acceptability is processed on the pump-curve facts for the following criteria:

- Flow rate for a pump-curve fact corresponds at less than or equal to the maximum acceptable discharge and suction velocity (V_{max}).

- Efficiency for a pump-curve fact corresponds within the range of minimum and maximum acceptable pump efficiency.

- Rotational speed (RPM) for a pump-curve fact corresponds at less than or equal to the maximum permissible rotational velocity.

The pump performance envelope produced by these rules is illustrated in Figure 4.
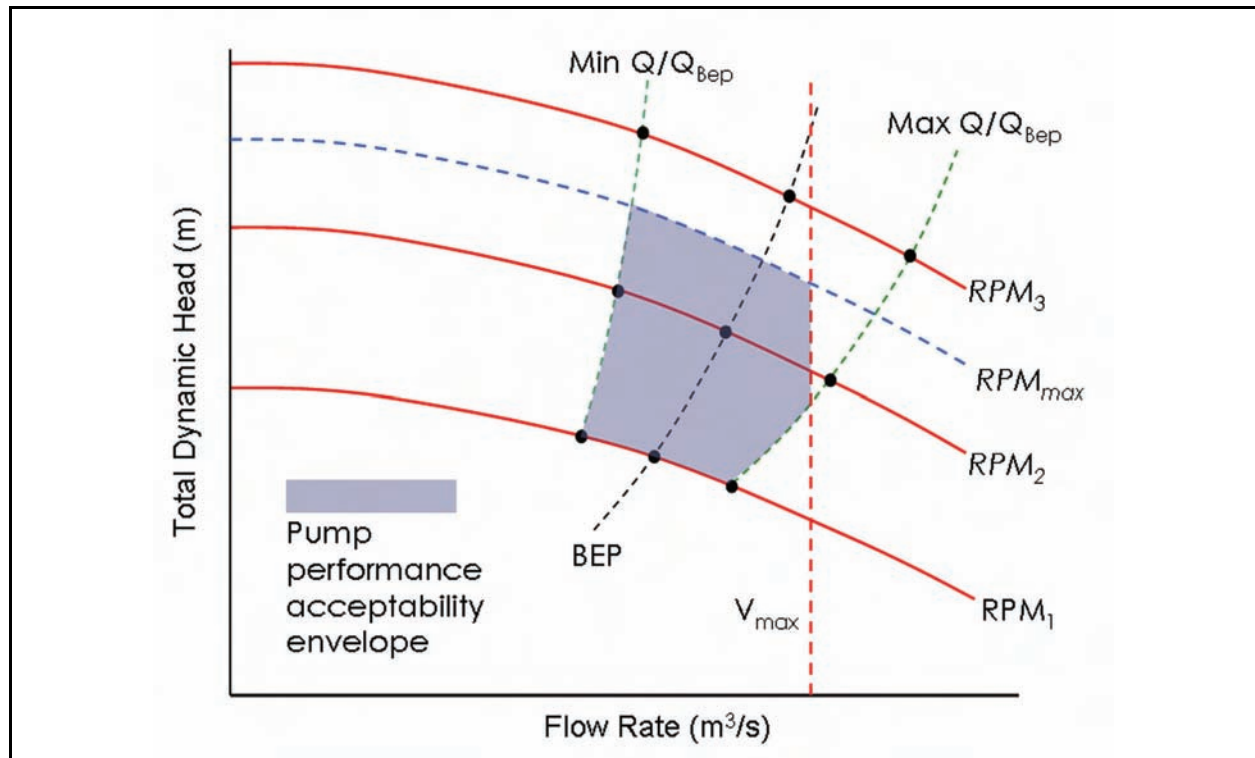
Figure 4. Pump performance envelope

PLOP Program Input Validity. When creating system-data facts for the program to process, it is important to make sure that the input is valid (i.e. not outside the scope for this pipeline application). Parameters that are not acceptable for the pumps considered are illustrated in the examples in Appendix A.

System Performance Output. System curves form the relation between flow-rate and head for a slurry of a given specific gravity. System-curve facts contain the data that composes the system curves for a slurry pump system. Each slurry density will form its own system curve calculated from the governing principles determined by Wilson et al. The intersection between a pump curve and a system curve represents the performance point where a pump will operate for a given material and pipe system. These system curves and performance points are illustrated in Figure 5. System curve facts also contain the data for available net positive suction head (NPSHA) or the absolute pressure head computed at the pump intake. NPSHA must be greater than the required net positive suction head (NPSHR) for a given pump to prevent the onset of cavitation.
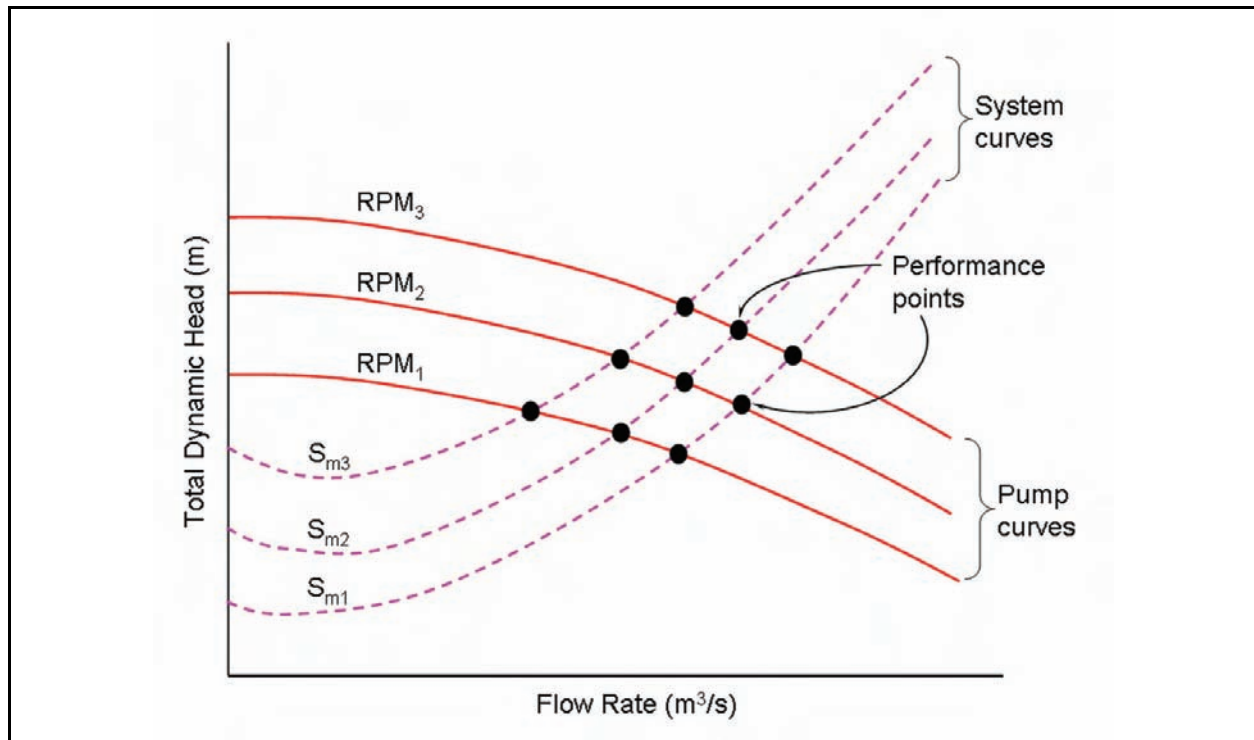
Figure 5. System and pump curves and their corresponding performance points

System rules on acceptable pump-data facts produce corresponding system-curve-data facts calculating the following variables:

- System head: Dynamic pressure head required to pump the slurry through the pipeline system at the given flow rate and slurry density.
- NPSHA: Net positive suction head available (NPSHA). Pressure head at the pump intake for the given flow rate and slurry density.
- Head difference: The difference between the system head and pump head at the given flow rate and density.

  A head difference greater than zero signifies that the system requires more head than the pump can produce at a given flow rate and slurry density and vice versa. The system will perform where the system and pump head are equal (i.e., head-difference = 0). However, no

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fact will likely compute zero head difference. Therefore, the performance point must be interpolated.

Interpolation is performed on the two system curve data facts that have positive and negative head-difference values closest to zero and the pump-data facts with the corresponding flow rates as illustrated in Figure 6.
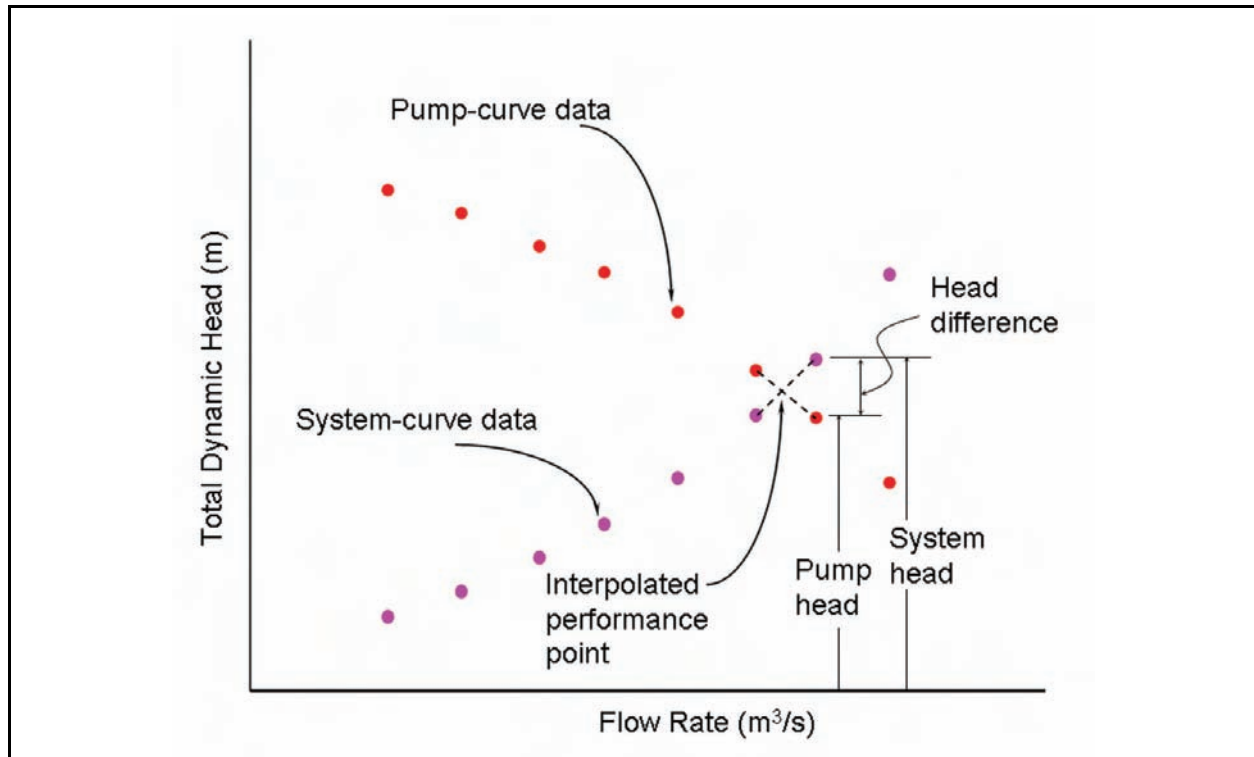
Figure 6. Pump performance interpolation

Performance flow rate, head, efficiency, NPSHR, and NPSHA are all interpolated from these facts from one rule. The performance points for the pump and pipeline setup are then asserted as pump-performance facts that store each performance point according to:

o   Sm

o   Pump number

o   Flow rate

o   Head

o   Power

o   eff

o   RPM

o   NPSHA

o   NPSHR

o   SEC

o   Acceptability

- Power: Power required to pump the slurry at the given flow rate and density. Power is typically measured in horsepower.

- SEC: Specific energy consumption (SEC). Measurement of the power used to transport dry solid material at the given flow rate over the given pipeline length. SEC is typically measured in Hp-Hr/ton-mi.

Performance points are then checked for cavitation. A rule is executed to identify pump-performance facts where the NPSHA is less than the NPSHR. Facts that satisfy this requirement are labeled as unacceptable and are output to the cavitation-output file in Table 1.

This output information will signify which pump settings (RPM and S_m) for a particular pump will induce cavitation.

Table 1
Pump Settings That Will Induce Cavitation

Cavitation Occurrence		
Pump	RPM	S_m
3	550	1.22
3	550	1.24
3	550	1.26
3	550	1.28
3	550	1.3
3	550	1.32

Pump-performance facts that are not susceptible to cavitation are output as the acceptable pump performance points shown in Appendix B. PLOP produces the performance points for each pump at each pump RPM for each slurry relative density.

To optimize pipeline operation efficiency, the pump RPM that produces the minimum specific energy consumption (SEC) for a given relative density is determined by PLOP. A rule within the PLOP program filters out the pump-performance fact for each pump at each relative density whose RPM corresponds to the minimum SEC value. These facts are then output as the optimum pump RPB settings shown in Table 2. Pump-performance facts that have insufficient NPSHA to prevent cavitation are omitted from this table even though they may correspond to a lower SEC. This output tabulates the optimum output efficiency that a pump can produce for a given pipeline system and slurry density. The SEC is defaulted to 999 for slurry relative densities of 1.0 since clear water would correspond to infinite specific energy consumption.

Table 2
Optimum Pump RPM Settings

Optimum Pump RPM Setting				
Pump	Sm	RPM	SEC	Eff
3	1	550	999	0.846
3	1.02	550	6.487	0.8494
3	1.04	550	3.296	0.8528
3	1.06	550	2.232	0.8544
3	1.08	500	1.425	0.874
3	1.1	500	1.158	0.8753
3	1.12	500	0.98	0.8766
3	1.14	500	0.852	0.8778
3	1.16	500	0.757	0.8791
3	1.18	500	0.682	0.8803
3	1.2	500	0.623	0.8815
3	1.22	500	0.574	0.8826
3	1.24	500	0.533	0.8837
3	1.26	500	0.499	0.8857
3	1.28	500	0.469	0.8879
3	1.3	500	0.444	0.8901
3	1.32	500	0.421	0.8921

Maximum pump efficiency does not necessarily correspond to minimum specific energy consumption. Slurry pumps, however, are designed to minimize this imbalance, and maximum attainable efficiency can correspond to the minimum SEC.

PLOP PROGRAM INPUT VALIDITY: The slurry transport text by Wilson el al. (1997) presents an example slurry pump curve that was used to verify the validity of the PLOP program by comparing the pump performance results obtained by both the PLOP program and by manual analytic solution. The example pump curve is shown in Figure 7. The example pipeline and material characteristics are as follows:

d_{50}	= 0.7 mm
d_{85}	= 1.0 mm
S_m	= 1.36
Pipeline diameter	= 0.65 m
Elevation difference	= 17 m
Digging depth	= 0.8 m
Pipeline length	= 938 m
Suction length	= 10 m
Equivalent length	= 45.8 m
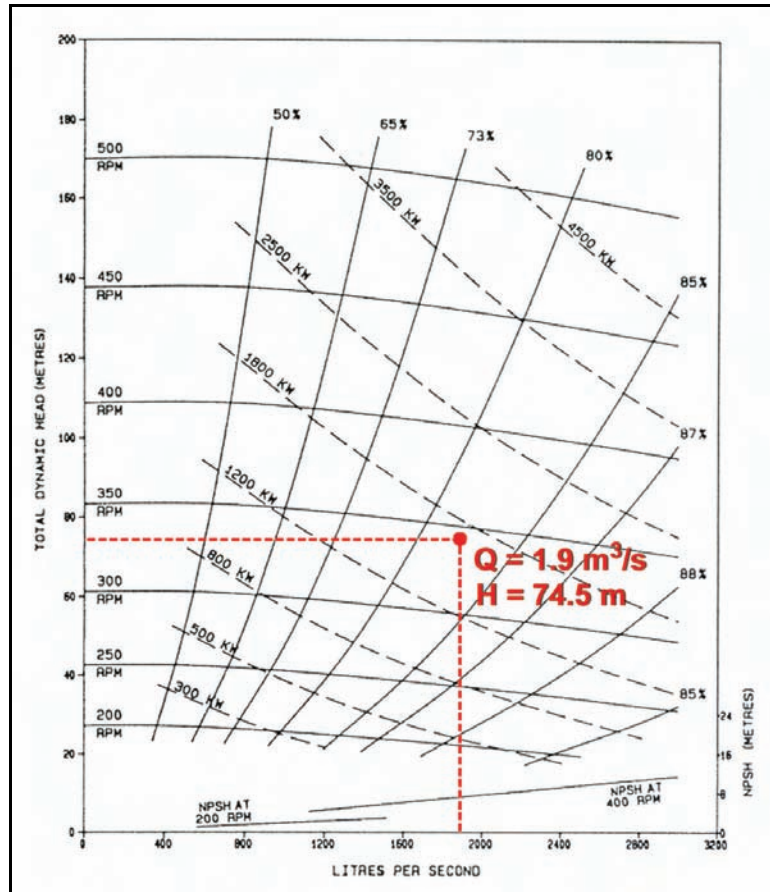
Figure 7. Example pump curve

For simplicity, the flow rate for the example is fixed at 1.9 m³/s. The pump performance parameters, shown in Table 3, were determined analytically and by the PLOP program.

PLOP determined higher performance values for the example pump due to limitations associated with interpolation. However, the general consistency of the

Table 3
Example Pump Performance Calculated by Analytical Solution and PLOP

Parameter	Analytical Solution	PLOP Output
Flow rate (Q) m³/s	1.9	2.01
Head (m)	74.5	76.4
RPM	345	350
Power (kW)	2303	2373
NPSHA (m)	3.20	2.74
SEC (Hp-hr/ton-mi)	0.98	1.05

two solutions suggests the accuracy and validity of the PLOP program to a reasonable degree. The pump performance example is discussed in greater detail in Appendix C.

RESULTS: Pipeline and slurry pump governing principles and theories were successfully implemented in the PLOP program. PLOP output was consistent with the example problem presented by Wilson et al. (1997) despite some variation. These results form an encouraging cornerstone in advancing the implementation of DODSS.

PLOP Capabilities/Limitations. Rules-based programming is the primary advantage of CLIPS towards this application. Slurry transport using centrifugal pumps is inherently a complex decision-making process. It is based not only on physical principles but also on widely accepted standards set by the industry. Expert languages such as CLIPS simplify decision-making programming through rules-based execution of input. CLIPS source code can be easily expanded upon without having to modify the existing source code. The PLOP program can be developed far more effectively and efficiently by building on the existing source code. The CLIPS source code for PLOP is shown in Appendix D.

Further Developments. PLOP is suited for the decision-making process of slurry transport applications. Such decision-making parameters are quite vast in pipeline dredging. Further expansion of PLOP capability would be to include pipeline dredge factors included in CUTPRO such as bank efficiency and dredge efficiency (How much time and effort is actually spent transporting solids). Cost-effectiveness is an inherent decision-making process that considers cost factors other than transport efficiency such as unit cost/hour and mobilization/demobilization costs. Such factors would be useful in determining the optimization for an entire pipeline operation.

Currently, CLIPS is not capable of graphics output that is often helpful with pump applications. Any future endeavor to incorporate a graphic output associated with PLOP would require integrating the current PLOP program with graphical software.

CONCLUSIONS: Studies conducted at ERDC have shown that in addition to performing conventional numerical procedures, CLIPS is capable of incorporating expert and heuristic knowledge into an application source code. Preliminary testing of PLOP indicates that further development of this program is warranted and the outline for future development is apparent.

POINTS OF CONTACT: For additional information on PLOP, contact Derek Wilson (601-634-4174, *Derek.A.Wilson@erdc.usace.army.mil*) or the Program Manager of the Dredging Operations and Environmental Research Program, Dr. Todd S. Bridges (601-634-3626, *Todd.S.Bridges@erdc.usace.army.mil*). This technical note should be cited as follows:

> Wilson, D. (2006). "Pipeline Optimization Program (PLOP)," *DOER Technical Notes Collection* (ERDC TN-DOER-T5), U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://el.erdc.usace.army.mil/dots/doer/doer.html

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Scott, S. H. (2000). "Application of dredge monitoring systems to dredge contract administration quality assurance," *DOER Technical Notes Collection* (ERDC TN-DOER-I3), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

Wilson, K. C., Addie, G. R., Sellgren, A., and Clift, R. (1997). *Slurry transport using centrifugal pumps.* Blackie Academic & Professional, London.

Appendix A: Examples of Parameters Not Acceptable for the Pumps

Elevation difference = 10.0 m
Digging depth = 3.0 m
Pipe length = 200.0 m
Equivalent length = 10.0 m
Pipe diameter = 0.609 m
Suction length = 6.0 m
Suction diameter = 0.609 m

Problem: Pipeline too short. System curve (dark black line) falls far below pump performance envelope
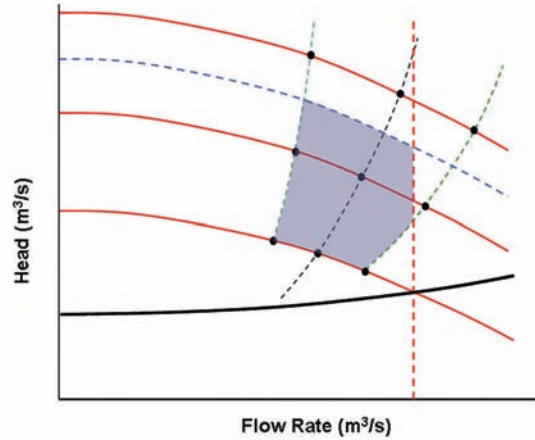
Elevation difference = 10.0 m
Digging depth = 3.0 m
Pipe length = 1,2000.0 m
Equivalent length = 10.0 m
Pipe diameter = 0.609 m
Suction length = 6.0 m
Suction diameter = 0.609 m

Problem: Pipeline too long. System curve (dark black line) overshoots above pump performance envelope
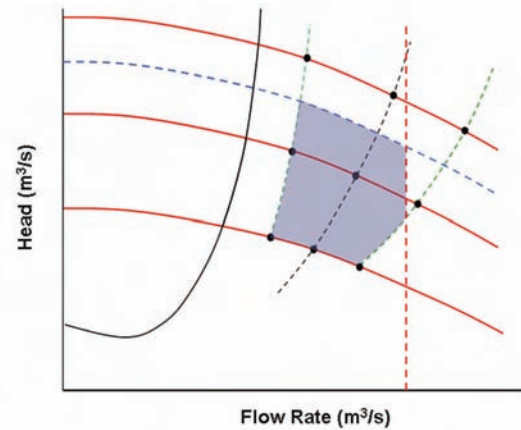
Elevation difference = 10.0 m
Digging depth = 30.0 m
Pipe length = 2,000.0 m
Equivalent length = 10.0 m
Pipe diameter = 0.609 m
Suction length = 6.0 m
Suction diameter = 0.609 m

Problem: Digging depth too deep. System curve (dark black line) overshoots above pump performance envelope
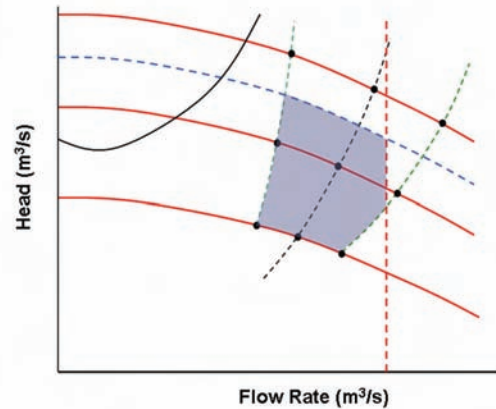
Elevation difference = 10.0 m
Digging depth = 1.0 m
Pipe length = 2,000.0 m
Equivalent length = 10.0 m
Pipe diameter = 0.609 m
Suction length = 6.0 m
Suction diameter = 0.609 m

Problem: Digging depth too shallow. System curve
(dark black line) falls far below pump performance
envelope
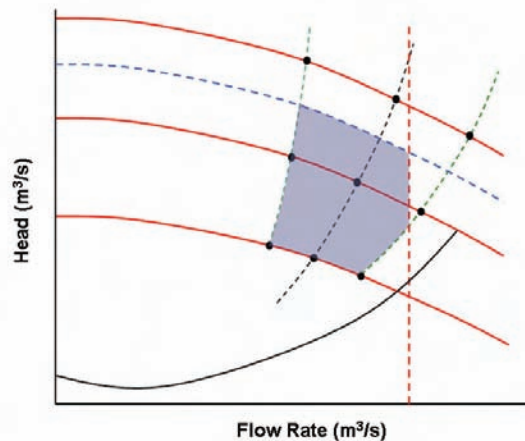
Elevation difference = 10.0 m
Digging depth = 3.0 m
Pipe length = 2,000.0 m
Equivalent length = 10.0 m
Pipe diameter = 0.609 m
Suction length = 6.0 m
Suction diameter = 0.609 m

Acceptable: System curve (dark black line) falls
within the pump performance envelope
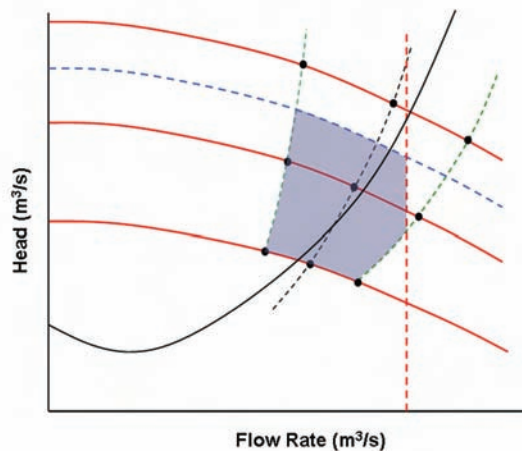
Appendix B: Sample Pump Performance Points

Table B.1 Pump Performance Output								
Pump	**Sm**	**Q**	**H**	**PWR**	**RPM**	**NPSHA**	**NPSHR**	**SEC**
1	1	1.42	70.78	1095	500	8.42	4.91	999.00
1	1	1.49	77.63	1239	525	8.23	5.52	999.00
1	1	1.57	84.46	1382	550	8.04	6.30	999.00
1	1.02	1.42	70.53	1119	500	8.15	5.00	5.95
1	1.02	1.50	77.35	1266	525	7.96	5.60	6.53
1	1.02	1.58	84.15	1427	550	7.77	6.43	7.10
1	1.04	1.43	70.28	1144	500	7.89	5.09	3.02
1	1.04	1.51	77.07	1294	525	7.70	5.69	3.32
1	1.04	1.59	83.84	1524	550	7.51	6.58	3.61
1	1.06	1.44	70.04	1168	500	7.64	5.18	2.05
1	1.06	1.52	76.80	1321	525	7.45	5.80	2.24
1	1.06	1.60	83.54	1622	550	7.25	6.72	2.44
1	1.08	1.45	69.80	1193	500	7.40	5.24	1.56
1	1.08	1.53	76.53	1349	525	7.20	5.91	1.71
1	1.08	1.61	83.24	1723	550	7.01	6.86	1.86
1	1.1	1.38	63.38	1059	475	7.35	4.62	1.15
1	1.1	1.46	69.57	1217	500	7.16	5.31	1.27
1	1.1	1.54	76.26	1376	525	6.97	6.02	1.39
1	1.1	1.62	82.95	1824	550	6.77	7.00	1.51
1	1.12	1.39	63.18	1080	475	7.12	4.70	0.98
1	1.12	1.47	69.33	1242	500	6.94	5.37	1.07
1	1.12	1.55	76.00	1404	525	6.74	6.13	1.17
1	1.12	1.63	82.66	1927	550	6.54	7.14	1.28
1	1.14	1.40	62.99	1102	475	6.90	4.77	0.85
1	1.14	1.48	69.11	1266	500	6.72	5.43	0.93
1	1.14	1.56	75.75	1431	525	6.52	6.24	1.02
1	1.14	1.64	82.38	2031	550	6.32	7.27	1.11
1	1.16	1.41	62.79	1123	475	6.69	4.85	0.75
1	1.16	1.49	68.88	1291	500	6.51	5.49	0.83
1	1.16	1.57	75.50	1459	525	6.31	6.34	0.91
1	1.18	1.42	62.60	1145	475	6.49	4.92	0.68
1	1.18	1.50	68.66	1315	500	6.30	5.55	0.74
1	1.18	1.58	75.25	1516	525	6.10	6.45	0.82
1	1.2	1.42	62.42	1166	475	6.30	4.99	0.62

Table B.1 Pump Performance Output								
Pump	**Sm**	**Q**	**H**	**PWR**	**RPM**	**NPSHA**	**NPSHR**	**SEC**
1	1.2	1.50	68.45	1340	500	6.11	5.60	0.68
1	1.2	1.59	75.01	1620	525	5.90	6.56	0.74
1	1.22	1.43	62.24	1188	475	6.11	5.06	0.57
1	1.22	1.51	68.24	1365	500	5.92	5.67	0.63
1	1.22	1.59	74.78	1726	525	5.71	6.67	0.69
1	1.24	1.44	62.06	1210	475	5.92	5.12	0.53
1	1.24	1.52	68.03	1389	500	5.73	5.75	0.58
1	1.24	1.60	74.55	1831	525	5.52	6.78	0.64
1	1.26	1.44	61.88	1231	475	5.74	5.19	0.50
1	1.26	1.53	67.83	1414	500	5.55	5.84	0.54
1	1.26	1.61	74.32	1938	525	5.34	6.89	0.60
1	1.28	1.45	61.71	1253	475	5.57	5.23	0.47
1	1.28	1.53	67.63	1439	500	5.38	5.92	0.51
1	1.28	1.62	74.11	2045	525	5.17	7.00	0.56
1	1.3	1.46	61.55	1275	475	5.41	5.28	0.44
1	1.3	1.54	67.44	1463	500	5.21	6.00	0.48
1	1.3	1.63	73.89	2152	525	5.00	7.10	0.53
1	1.32	1.46	61.39	1296	475	5.24	5.32	0.42
1	1.32	1.55	67.26	1488	500	5.05	6.08	0.46
1	1.32	1.63	73.69	2259	525	4.83	7.20	0.50
2	1	1.40	69.33	1111	475	8.46	5.47	999.00
2	1	1.48	76.11	1276	500	8.28	6.22	999.00
2	1	1.56	83.47	1443	525	8.07	7.11	999.00
2	1	1.63	90.82	2004	550	7.87	8.27	999.00
2	1.02	1.41	69.08	1136	475	8.19	5.57	5.83
2	1.02	1.49	75.82	1305	500	8.00	6.30	6.40
2	1.02	1.57	83.14	1474	525	7.80	7.25	7.01
2	1.04	1.42	68.83	1161	475	7.93	5.67	2.96
2	1.04	1.50	75.53	1333	500	7.74	6.38	3.25
2	1.04	1.58	82.82	1525	525	7.54	7.39	3.56
2	1.06	1.43	68.58	1186	475	7.68	5.77	2.00
2	1.06	1.51	75.24	1362	500	7.49	6.45	2.20
2	1.06	1.59	82.50	1649	525	7.28	7.55	2.41
2	1.08	1.44	68.34	1211	475	7.44	5.86	1.53
2	1.08	1.51	74.96	1390	500	7.25	6.56	1.67
2	1.08	1.60	82.19	1776	525	7.04	7.71	1.84

Table B.1 Pump Performance Output

Pump	Sm	Q	H	PWR	RPM	NPSHA	NPSHR	SEC
2	1.1	1.44	68.10	1236	475	7.21	5.96	1.24
2	1.1	1.52	74.69	1419	500	7.01	6.68	1.36
2	1.1	1.61	81.89	1905	525	6.80	7.86	1.49
2	1.12	1.45	67.86	1261	475	6.98	6.03	1.05
2	1.12	1.53	74.42	1447	500	6.79	6.80	1.15
2	1.12	1.62	81.59	2036	525	6.57	8.02	1.26
2	1.14	1.46	67.63	1286	475	6.76	6.09	0.91
2	1.14	1.54	74.15	1476	500	6.57	6.91	1.00
2	1.14	1.63	81.29	2168	525	6.35	8.17	1.10
2	1.16	1.38	60.78	716	400	6.76	5.29	0.73
2	1.16	1.38	60.78	916	425	6.76	5.29	0.73
2	1.16	1.38	60.78	1116	450	6.76	5.29	0.73
2	1.16	1.47	67.40	1311	475	6.55	6.16	0.81
2	1.16	1.55	73.89	1505	500	6.36	7.03	0.89
2	1.16	1.63	81.00	2302	525	6.14	8.31	0.97
2	1.18	1.39	60.59	731	400	6.55	5.36	0.66
2	1.18	1.39	60.59	934	425	6.55	5.36	0.66
2	1.18	1.39	60.59	1138	450	6.55	5.36	0.66
2	1.18	1.48	67.18	1337	475	6.35	6.22	0.73
2	1.18	1.56	73.63	1533	500	6.15	7.14	0.80
2	1.2	1.40	60.41	745	400	6.36	5.44	0.60
2	1.2	1.40	60.41	952	425	6.36	5.44	0.60
2	1.2	1.40	60.41	1159	450	6.36	5.44	0.60
2	1.2	1.48	66.96	1362	475	6.15	6.28	0.66
2	1.2	1.57	73.38	1562	500	5.95	7.25	0.73
2	1.22	1.40	60.23	760	400	6.17	5.52	0.55
2	1.22	1.40	60.23	971	425	6.17	5.52	0.55
2	1.22	1.40	60.23	1181	450	6.17	5.52	0.55
2	1.22	1.49	66.74	1387	475	5.96	6.34	0.61
2	1.22	1.57	73.14	1591	500	5.76	7.36	0.67
2	1.24	1.41	60.05	775	400	5.99	5.59	0.51
2	1.24	1.41	60.05	989	425	5.99	5.59	0.51
2	1.24	1.41	60.05	1203	450	5.99	5.59	0.51
2	1.24	1.50	66.53	1413	475	5.78	6.40	0.57
2	1.24	1.58	72.90	1713	500	5.58	7.48	0.62
2	1.26	1.42	59.87	790	400	5.81	5.66	0.48

Table B.1	Pump Performance Output							
Pump	Sm	Q	H	PWR	RPM	NPSHA	NPSHR	SEC
2	1.26	1.42	59.87	1007	425	5.81	5.66	0.48
2	1.26	1.42	59.87	1225	450	5.81	5.66	0.48
2	1.26	1.51	66.33	1438	475	5.60	6.46	0.53
2	1.26	1.59	72.67	1842	500	5.40	7.59	0.58
2	1.28	1.42	59.70	805	400	5.64	5.73	0.45
2	1.28	1.42	59.70	1026	425	5.64	5.73	0.45
2	1.28	1.42	59.70	1246	450	5.64	5.73	0.45
2	1.28	1.51	66.13	1463	475	5.43	6.54	0.50
2	1.28	1.60	72.45	1970	500	5.22	7.71	0.55
2	1.3	1.43	59.54	820	400	5.47	5.80	0.43
2	1.3	1.43	59.54	1044	425	5.47	5.80	0.43
2	1.3	1.43	59.54	1268	450	5.47	5.80	0.43
2	1.3	1.52	65.94	1488	475	5.26	6.63	0.47
2	1.3	1.60	72.23	2100	500	5.05	7.82	0.52
2	1.32	1.43	59.38	835	400	5.31	5.86	0.41
2	1.32	1.43	59.38	1062	425	5.31	5.86	0.41
2	1.32	1.43	59.38	1290	450	5.31	5.86	0.41
2	1.32	1.53	65.75	1514	475	5.10	6.71	0.45
2	1.32	1.61	72.02	2229	500	4.89	7.93	0.49
3	1	1.42	70.91	1098	525	8.42	4.43	999.00
3	1	1.49	77.14	1226	550	8.25	4.93	999.00
3	1.02	1.43	70.67	1123	525	8.15	4.52	5.96
3	1.02	1.50	76.88	1253	550	7.97	5.00	6.49
3	1.04	1.44	70.45	1147	525	7.89	4.60	3.03
3	1.04	1.51	76.62	1280	550	7.71	5.07	3.30
3	1.06	1.45	70.22	1171	525	7.63	4.68	2.05
3	1.06	1.52	76.37	1307	550	7.46	5.17	2.23
3	1.08	1.38	63.82	1056	500	7.57	4.11	1.43
3	1.08	1.46	70.00	1195	525	7.39	4.73	1.56
3	1.08	1.53	76.13	1334	550	7.21	5.27	1.70
3	1.1	1.39	63.63	1077	500	7.34	4.18	1.16
3	1.1	1.46	69.78	1220	525	7.16	4.79	1.27
3	1.1	1.54	75.89	1361	550	6.98	5.37	1.38
3	1.12	1.40	63.44	1099	500	7.11	4.25	0.98
3	1.12	1.47	69.56	1244	525	6.93	4.85	1.07
3	1.12	1.55	75.65	1388	550	6.75	5.47	1.17

Table B.1 Pump Performance Output

Pump	Sm	Q	H	PWR	RPM	NPSHA	NPSHR	SEC
3	1.14	1.40	63.26	1121	500	6.90	4.32	0.85
3	1.14	1.48	69.35	1269	525	6.71	4.90	0.93
3	1.14	1.56	75.41	1415	550	6.53	5.57	1.02
3	1.16	1.41	63.07	1142	500	6.69	4.39	0.76
3	1.16	1.49	69.14	1293	525	6.50	4.96	0.83
3	1.16	1.57	75.18	1443	550	6.32	5.66	0.90
3	1.18	1.42	62.89	1164	500	6.48	4.46	0.68
3	1.18	1.50	68.94	1318	525	6.30	5.01	0.75
3	1.18	1.57	74.96	1470	550	6.11	5.76	0.81
3	1.2	1.43	62.72	1186	500	6.29	4.52	0.62
3	1.2	1.51	68.73	1342	525	6.10	5.06	0.68
3	1.2	1.58	74.74	1551	550	5.91	5.86	0.74
3	1.22	1.43	62.55	1208	500	6.10	4.59	0.57
3	1.22	1.52	68.54	1367	525	5.91	5.14	0.63
3	1.22	1.59	74.52	1635	550	5.72	5.97	0.68
3	1.24	1.44	62.38	1229	500	5.91	4.65	0.53
3	1.24	1.52	68.35	1391	525	5.72	5.22	0.58
3	1.24	1.60	74.31	1719	550	5.53	6.07	0.64
3	1.26	1.45	62.21	1251	500	5.73	4.70	0.50
3	1.26	1.53	68.16	1416	525	5.54	5.30	0.55
3	1.26	1.61	74.10	1804	550	5.35	6.17	0.59
3	1.28	1.46	62.05	1273	500	5.56	4.74	0.47
3	1.28	1.54	67.98	1440	525	5.37	5.37	0.51
3	1.28	1.62	73.90	1889	550	5.17	6.27	0.56
3	1.3	1.38	56.43	1126	475	5.57	4.15	0.40
3	1.3	1.46	61.89	1295	500	5.39	4.78	0.44
3	1.3	1.55	67.80	1465	525	5.20	5.45	0.49
3	1.3	1.62	73.70	1975	550	5.00	6.36	0.53
3	1.32	1.39	56.30	1145	475	5.41	4.20	0.38
3	1.32	1.47	61.74	1317	500	5.23	4.82	0.42
3	1.32	1.55	67.63	1489	525	5.04	5.52	0.46
3	1.32	1.63	73.51	2060	550	4.84	6.45	0.50

Appendix C: Pump Performance Example

d_{50}	=	0.7	mm
d_{85}	=	1.0	mm
Sm	=	1.36	
Pipeline diameter(D)	=	0.65	m
Elevation difference(Δz)	=	17	m
Digging depth(Δz_d)	=	0.8	m
Pipeline Length(L)	=	938	m
Suction Length(l_s)	=	10	m
Equivalent Length(l_{eq})	=	45.8	m
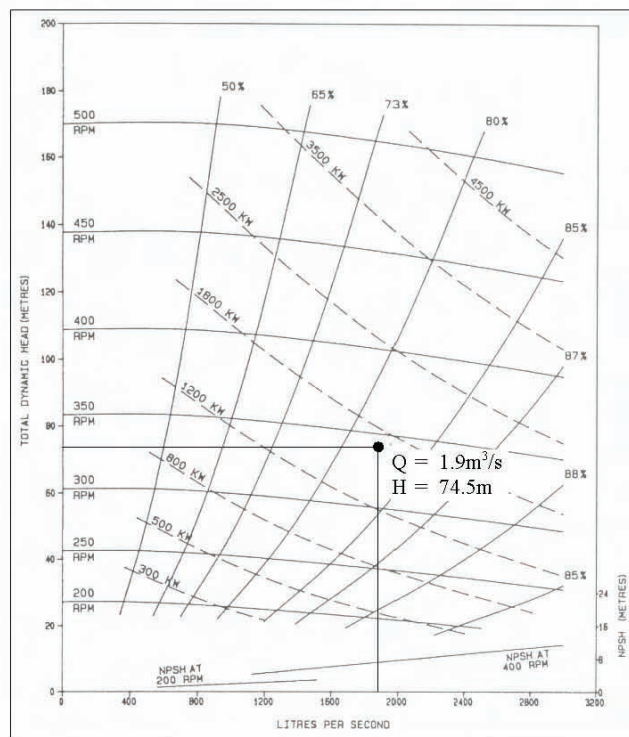
Figure C.1. Example Pump Curve

$$Q = 1.9\, m^3\big/s$$

$$V_m = \frac{4Q}{\pi D^2} = \frac{41.9}{\pi\, 0.65^2} = 5.7\, m\big/s$$

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$$v_{ts} = 1.73\sqrt{g d_{50}(S_s - 1)} = 1.73\sqrt{9.81(0.0007)(2.65-1)} = 0.184\,m/s$$

$$v_t = \varepsilon v_{ts}$$

$$\varepsilon \approx 0.4$$

$$v_t = 0.4(0.184) = 0.11\,m/s$$

$$v'_t = v_t(1-C_v)^n$$

$$n \approx 2.4$$

$$v'_t = 0.11(1-0.22)^{2.4} = 0.06\,m/s$$

$$w = 0.9 v'_t + 2.7\left[\frac{(\rho_s - \rho_f)}{\rho_f^2}g\mu\right]^{\frac{1}{3}}$$

$$\mu = 10^{-3}\frac{Ns^2}{m}$$

$$w = 0.9(0.006) + 2.7\left[\frac{(2650-1000)}{1000^2}9.81\times10^{-3}\right]^{\frac{1}{3}} = 0.123\,m/s$$

$$V_{50} = w\left(\frac{8}{f}\right)^{\frac{1}{2}}\cosh\left[\frac{60 d_{50}}{D}\right]$$

$$f = 0.02$$

$$V_{50} = 0.123\left(\frac{8}{0.02}\right)^{\frac{1}{2}}\cosh\left[\frac{60(0.0007)}{0.65}\right] = 2.46\,m/s$$

$$i_m = \frac{f V_m^2}{2gD} + 0.22(S_m - 1)\left(\frac{V_{50}}{V_m}\right)^{1.7} = \frac{0.02(5.7)^2}{2(9.81)0.65} + 0.22(1.36-1)\left(\frac{2.46}{5.7}\right)^{1.7} = 0.07$$

$$H = \frac{i_m}{s_m}(L + l_{eq} + l_s) + \Delta z_d + \Delta z + \frac{V_m^2}{2g} - \frac{\Delta z_d}{S_m} = \frac{0.07}{1.36}(938+458+10) + 0.8 + 17 + \frac{5.7^2}{2(9.81)} - \frac{0.8}{1.36} = 745\,m$$

$$NPSHA = \frac{H_{bar} - H_{vac}}{S_m} - \frac{i_m(l_{eq} + l_s)}{s_m} - \Delta z_d - \frac{V_m^2}{2g} + \frac{\Delta z_d}{S_m} = \frac{10.3 - 0.24}{1.36} - \frac{0.07(10+458)}{1.36} - 0.8 - \frac{5.7^2}{2(9.81)} + \frac{0.8}{1.36} = 3.2\,m$$

From the pump curve, the efficiency and RPM are determined at 82% and 345, respectively, for the calculated head and flow rate.

$$Power = \frac{S_m \rho_w gHQ}{eff} = \frac{1.36 \cdot 1000 \cdot 9.81 \cdot 74.5 \cdot 1.9}{0.82} = 2303 kW$$

$$SEC = \frac{5.33 S_m H}{S_s c_v L} = \frac{5.33 \cdot 1.36 \cdot 74.5}{2.65 \cdot 0.221 \cdot 938} = 0.983 \frac{Hp \cdot Hr}{ton \cdot mile}$$

Appendix D: CLIPS Source Code for PLOP

(defglobal ?*S-solid*	= 2.65)	;specific gravity of solid
(defglobal ?*S-fluid*	= 1.00)	;specific gravity of fluid
(defglobal ?*S-insitu*	= 1.32)	;specific gravity of insitu material (consolidated)
(defglobal ?*density-fluid*	= (* ?*S-fluid* 1000))	;density of carrier fluid [kg/cu.m]
(defglobal ?*density-solid*	= (* ?*S-solid* 1000))	;density of solid material [kg/cu.m]
(defglobal ?*gravity*	= 9.81)	;acceleration of gravity [m/sq.s]
(defglobal ?*dyn-visc*	= 1.e-3)	;dynamic viscosity of fluid [N sq.s/m]
(defglobal ?*fw*	= 0.015)	;friction factor of pipe for water
(defglobal ?*roughness*	= 4.6e-5)	;roughness coefficient for steel pipe [m]
(defglobal ?*Hbar*	= 10.34)	;Atmospheric pressure head in meters of water
(defglobal ?*Hvap*	= 0.24)	;Vapor Pressure head of water in meters of water

```
;THIS FUNCTION CALCULATES THE SETTLING VELOCITY OF A PARTICLE IN A FLUID BASED ON THE STOKES
RELATIONSHIP OF
;DIMENSIONLESS DIAMETER AND VELOCITY
(deffunction vt-calc (?diameter ?cv)
        (bind ?epsilon 0.6)  ;TYPICAL EPSILON VALUE FOR SAND
;        (bind ?d-star (* ?diameter (** (* ?*density-fluid* (- ?*density-solid* ?*density-fluid*) ?*gravity* (** ?*dyn-visc* -2.))
(/ 1. 3.))))
;        (bind ?w (log10 ?d-star))
;        (bind ?x (log10 (+ (/ (** ?d-star 2) 18) (* -3.1234e-4 (** ?d-star 5)) (* 1.6415e-6 (** ?d-star 8)) (* -7.278e-10 (**
?d-star 11)))))
;
;        (if (> ?d-star 3.8) then (bind ?x (+ -1.5446 (* 2.9162 ?w) (* -1.0432 (** ?w 2)))))
;        (if (> ?d-star 7.58) then (bind ?x (+ -1.64758 (* 2.94786 ?w) (* -1.09703 (** ?w 2)) (* 0.17129 (** ?w 3)))))
;        (if (> ?d-star 227) then (bind ?x (+ 5.1837 (* -4.5103 ?w) (* 1.687 (** ?w 2)) (* -0.189135 (** ?w 3)))))
;        (bind ?vt-star (** 10 ?x))
;        (bind ?vts (* ?vt-star (** (* (- ?*density-solid* ?*density-fluid*) ?*gravity* (** ?*density-fluid* -2.) ?*dyn-visc*) (/ 1.
3.))))
        (bind ?vts 10.0)
        (bind ?vt (* ?epsilon ?vts))
        (bind ?Rep (* ?*density-fluid* ?vts ?diameter (/ 1.0 ?*dyn-visc*)))
        (if (<= ?Rep 0.2) then (bind ?n 4.6))
        (if (and (> ?Rep 0.2) (<= ?Rep 1.0)) then (bind ?n (* 4.4 (** ?Rep -0.3))))
        (if (and (> ?Rep 1.0) (<= ?Rep 500.0)) then (bind ?n (* 4.4 (** ?Rep -0.1))))
        (if (> ?Rep 500.0) then (bind ?n 2.4))
        (bind ?vht (* ?vt (** (- 1.0 ?cv) ?n)))
        (return ?vht)
)

(deffunction w-calc (?d ?cv)
        (bind ?vt  (vt-calc ?d ?cv))
        (bind ?w  (+ (* 0.9 ?vt) (* 2.7 (** (/ (* (- ?*density-solid* ?*density-fluid*) ?*gravity* ?*dyn-visc*) (** ?*density-
fluid* 2)) (/ 1 3)))))
        (return ?w)
)

(deffunction m-calc (?d50 ?d85 ?D ?cv)
        (bind ?w85 (w-calc ?d85 ?cv))
        (bind ?w50 (w-calc ?d50 ?cv))
        (bind ?sigma-s (log10 (/ (* ?w85 (cosh (/ (* 60 ?d85) ?D))) (* ?w50 (cosh (/ (* 60 ?d50) ?D))))))
        (bind ?m (** (+ 0.25 (* 13.0 (** ?sigma-s 2))) -0.50))
        (if (< ?m 0.25) then (bind ?m 0.25))
        (if (> ?m 1.70) then (bind ?m 1.70))
        (return ?m)
)


(deffunction v50-calc (?d50 ?D ?cv)
        (bind ?w (w-calc ?d50 ?cv))
        (bind ?v50 (* ?w (sqrt (/ 8 ?*fw*)) (cosh (/ (* 60 ?d50) ?D))))
```

```
                (return ?v50)
)


(deffunction iw-calc (?vm ?D)
        (bind ?iw (/ (* ?*fw* ?vm ?vm) (* 2.0 ?D ?*gravity*)))
        (return ?iw)
)



(deffunction vsm-calc (?D)
        (bind ?vsm (* (** (/ .018 ?*fw*) 0.13) (sqrt (* 2 ?*gravity* ?D (- ?*S-solid* ?*S-fluid*)))))
        (return ?vsm)
)

(deffunction vsm30degree-calc (?D)
        (bind ?vsm          (vsm-calc ?D))
        (bind ?delta-D       0.33)
        (bind ?vsm30          (+ ?vsm (* ?delta-D (sqrt (* 2 ?*gravity* ?D (- ?*S-solid* ?*S-fluid*))))))
        (return ?vsm30)
)

(deffunction w30degree-calc (?d ?cv)
        (bind ?theta  (/ (pi) 6))
        (bind ?vt  (* (vt-calc ?d ?cv) (cos ?theta)))
        (bind ?w   (+ (* 0.9 ?vt) (* (** (cos ?theta) (/ 1 3)) 2.7 (** (/ (* (- ?*density-solid* ?*density-fluid*) ?*gravity* ?*dyn-
visc*) (** ?*density-fluid* 2)) (/ 1 3)))))
        (return ?w)
)

(deffunction v50-30degree-calc (?d50 ?D ?cv)
        (bind ?w (w30degree-calc ?d50 ?cv))
        (bind ?v50 (* ?w (sqrt (/ 8 ?*fw*)) (cosh (/ (* 60 ?d50) ?D))))
        (return ?v50)
)

(deffunction im-iw-calc (?vm ?D ?d50 ?d85 ?cv)
        (bind ?v50          (v50-calc ?d50 ?D ?cv))
        (bind ?m  (m-calc ?d50 ?d85 ?D ?cv))
        (bind ?im-iw          (* (- ?*S-solid* 1) ?cv 0.22 (** (/ ?vm ?v50) ?m)))
)


(deffunction Re-calc (?vm ?D)
                (bind ?Re (* ?vm ?D ?*density-fluid* (/ 1 ?*dyn-visc*)))
                (bind ?log-Re        (log10 ?Re))
                (bind ?expo          (div ?log-Re 1))
                (bind ?coef          (mod ?log-Re 1))
                (bind ?new-expo (integer (** 10 ?expo)))
                (bind ?new-coef (round   (+ (** 10 ?coef) .001)))
                (bind ?new-Re         (* ?new-expo ?new-coef))
                (return ?new-Re)
)


(deffunction determine-pump-class (?d50 ?Sm)     ;DETERMINES PUMP CLASS FROM FIG 8.20
        (bind ?class 1)                                  ;POWER LAW FACTORS ESTIMATED FROM CURVES
        (if (>= ?Sm (* 1.0 (** ?d50 -0.0318))) then (bind ?class 2))
        (if (>= ?Sm (* 1.1 (** ?d50 -0.1824))) then (bind ?class 3))
        (if (>= ?Sm (* 1.2 (** ?d50 -0.2219))) then (bind ?class 4))
        (return ?class)
)

(open "c:/clips/dredge-pump/output-files/max-sec.txt" max-sec "w")
(open "c:/clips/dredge-pump/output-files/system-curves.txt" system-curve-data "w")
(open "c:/clips/dredge-pump/output-files/performance-points.txt" pump-performance-data "w")
(open "c:/clips/dredge-pump/output-files/performance-summary.txt" pump-performance-summary "w")
(open "c:/clips/dredge-pump/output-files/min-SEC-output.txt" min-SEC-summary "w")
(open "c:/clips/dredge-pump/output-files/accptbl-SEC-output.txt" other-SEC-summary "w")
```

```
(open "c:/clips/dredge-pump/output-files/cavitation-output.txt" cavitation-summary "w")
(printout pump-performance-data "pump,Sm,Q,H,PWR,RPM,NPSHA,NPSHR,SEC,acc" crlf)
(printout min-SEC-summary "Sm pump RPM SEC Eff" crlf)

;DEFTEMPLATES FOR INHERENT SYSTEM PARAMETERS



;MATERIAL-CHAR TEMPLATE SPECIFIES THE PERTINENT PHYSICAL ATTRIBUTES OF THE BED MATERIAL
;THE IN-SITU DENSITY OF MATERIAL IS ASSUMED TO BE THE MAXIMUM SLURRY DENSITY THAT WILL PASS
THROUGH THE P/L SYSTEM
(deftemplate material-char      (slot v50                    (default 0.00))              ;Stratification velocity of
material in meters per second
                                (slot d50                    (default 0.00025))  ;Particle size (m) where 50%
of particles are finer
                                (slot d85                    (default 0.00050))  ;Particle size (m) where 85%
of particles are finer
                                (slot xh                     (default 0.10))              ;mass fraction of
particles finer than 0.075mm
                                (slot Sm                     (default ?*S-insitu*));typical in-situ density of bed
material
)


;THE P/L SYSTEM DATA SPECIFIES THE GOVERNING ATTRIBUTES FOR PIPING AND PUMPING SYSTEM
;THIS INCLUDES THE BASIC GEOMETRY OF THE PIPING SYSTEM
(deftemplate system-data      (slot elevation-difference     (default 10.0))      ;Elevation Head in meters
                                (slot digging-depth          (default 03.0))              ;digging depth in
meters
                                (slot pipe-length            (default 2000.0))    ;Overall Pipe length in meters
                                (slot equivalent-length              (default 010.0))     ;equivalent lengths
due to flow constriction
                                (slot pipe-diameter          (default 0.609))     ;Pipe diameter in meters
                                (slot suction-length         (default 06.00))     ;Length of Pipe on Suction
side of pump
                                (slot suction-diameter               (default 0.609))     ;Suction Pipe
diameter in meters
)


;OPERATIONS PARAMETERS TEMPLATE SPECIFIES THE ACCEPTABLE OPERATING PARAMETERS FOR THE
PUMP SYSTEM
(deftemplate operation-parameters      ;THIS TEMPLATE WILL DEFINE THE EXTREME OPERATION PARAMETERS
                                (slot max-discharge-vel)                     ;FOR THE PUMP SYSTEM
                                (slot max-suction-vel)
                                (slot max-impeller-prph-speed)
                                (slot min-percent-QBEP)
                                (slot max-percent-QBEP)
)


;PUMP CURVE TEMPLATE ORGANIZES THE PUMP CURVE DATA INTO FACT FILES ACCORDING TO
ATTRIBUTES
(deftemplate pump-curve        (slot pump-number)
                                (slot flow-rate)
                                (slot head)
                                (slot NPSHR)
                                (slot RPM)
                                (slot power)
                                (slot eff)
                                (slot acceptability          (allowed-values yes no))
)

;THIS TEMPLATE  COMES IN HANDY WHEN IDENTIFYING THE BEP FOR A PUMP AT VARYING RPM
(deftemplate pump-BEP-char  (slot pump-number)
                                (slot RPM)
                                (slot eff-max)
                                (slot Qbep)
)
```

```
(deftemplate pump-op-limits    (slot class                        (allowed-values 1 2 3 4))
                               (slot max-discharge-vel            (type FLOAT) (range 0.0 50.0))
                               (slot max-suction-vel              (type FLOAT) (range 0.0 50.0))
                               (slot max-impeller-prph-speed      (type FLOAT) (range 0.0 100.0))
)


(deftemplate shell-type-limits-of-Qbep
               (slot class            (allowed-values 1 2 3 4))
               (slot shell-type       (allowed-values any annular semi-volute near-volute annular-obliqe)
                                      (default any))
               (multislot min-max-percent-QBEP (type FLOAT) (range 0.0 200.0))
)


(deftemplate system-curve    (slot Sm)
                                (slot pump-number)
                                (slot flow-rate)
                                (slot head)
                                (slot RPM)
                                (slot NPSHA)
                                (slot head-difference)

)


(deftemplate pump-performance    (slot Sm)
                                (slot pump-number)
                                (slot flow-rate)
                                (slot head)
                                (slot power)
                                (slot eff)
                                (slot RPM)
                                (slot NPSHA)
                                (slot NPSHR)
                                (slot SEC)
                                (slot acceptability)
)


(deftemplate min-SEC-performance-point    (slot pump-number)
                                (slot Sm)
                                (slot flow-rate)
                                (slot head)
                                (slot power)
                                (slot eff)
                                (slot RPM)
                                (slot SEC)
)


;Description:
;
;This CLIPS Code defines templates and facts for pump type suitability based on Wilson et al. Table 8.1.  This defines the
parameters in which certain pumps ;should operate based on industry standards.  The main attributes associated with
;pump suitability are the maximum permissible discharge and suction ;velocities [m/s], deviation from the Best Efficiency
Point (%), ;and impeller periphreal speed [m/s](speed at tip of impeller).  The factors determining ;these parameters are
the pump service ;class (1, 2, 3, 4) and shell type (annular, semi-volute, etc.).FACTS ARE CALLED FROM PUMP-
SHELL-ATTRIBUTES.FACTS
;*******************************************************************************
;
;***************THIS RULE DETERMINES PUMP BEP PROPERTIES*********************************

(defrule determine-Qbep-for-each-pump-at-each-rpm
               (pump-curve (pump-number ?n) (RPM ?rpm) (flow-rate ?Qbep) (eff ?eff-max))
               (not (exists (pump-curve (pump-number ?n) (RPM ?rpm) (eff ?eff&:(> ?eff ?eff-max)))))
               (not (exists (pump-BEP-char (pump-number ?n) (RPM ?rpm))))
               =>
               (assert (pump-BEP-char (pump-number ?n) (RPM ?rpm) (Qbep ?Qbep)))
)


;*******************************************************************************
;
```

```
;**************THIS RULE DETERMINES PUMP CLASS BASED ON MATERIAL PROPERTIES*************

(defrule determine-pump-class
          (material-char (d50 ?d50) (Sm ?Sm) )
          =>
          (assert (pump-class (determine-pump-class ?d50 ?Sm)))
)



;*****************************************************************************************
;
;***************THIS RULE DETERMINES MIN-MAX OPERATION PARAMETERS BASED ON PUMP CLASS****
;***************NOTE:  VELOCITY IN PIPE = VELOCITY IN PUMP SUCTION AND DISCHARGE*********

(defrule find-min-max-op-parameters
          (pump-class ?class)
          (shell-type-limits-of-Qbep (class ?class) (shell-type semi-volute) (min-max-percent-QBEP ?min-Qbep ?max-
Qbep))
          (pump-op-limits (class ?class)          (max-discharge-vel ?max-dis-vel)
                                                  (max-suction-vel   ?max-suc-vel)
                                                  (max-impeller-prph-speed ?max-imp-vel)
          )
          =>
          (assert (operation-parameters          (max-discharge-vel ?max-dis-vel)
                                                  (max-suction-vel   ?max-suc-vel)
                                                  (max-impeller-prph-speed ?max-imp-vel)
                                                  (min-percent-QBEP ?min-Qbep)
                                                  (max-percent-QBEP ?max-Qbep)
                )
          )
)



;*****************************************************************************************
;
;***************THIS RULE DETERMINES DETERMINES THE OPERATING RANGE FOR EACH PUMP BASED**
;***************ON THE EXTREME OPERATION PARAMETERS     *********************************
;***************NOTE THAT:    IMPELLER DIAMETER = 0.8 M


(defrule determine-acceptable-pump-operating-ranges
               (system-data (pipe-diameter ?D))
               (operation-parameters          (max-discharge-vel ?max-dis-vel)
                                              (max-suction-vel   ?max-suc-vel)
                                              (max-impeller-prph-speed ?max-imp-vel)
                                              (min-percent-QBEP ?min-Qbep)
                                              (max-percent-QBEP ?max-Qbep))
               (pump-BEP-char (pump-number ?n) (RPM ?rpm) (Qbep ?Qbep))
               ?pump-curve <- (pump-curve (pump-number ?n) (flow-rate ?Q) (RPM ?rpm) (eff ?eff) (acceptability
~yes))
               =>
               (bind ?vm          (* 4 ?Q (/ 1 (pi) ?D ?D)))
               (bind ?vsm         (vsm-calc ?D))
               (bind ?imp-vel     (* ?rpm (pi) (/ 1 60.0) 0.8 ))
               (if (and    (<= ?vm ?max-dis-vel)       (<= ?vm ?max-suc-vel)
                                  (<= ?imp-vel ?max-imp-vel)
                                  (>= (/ ?Q ?Qbep) (/ ?min-Qbep 100))
                                  (<= (/ ?Q ?Qbep) (/ ?max-Qbep 100))
                                  (>= ?vm ?vsm))
               then
                                  (modify ?pump-curve (acceptability yes))
               )
)




(defrule determine-UNacceptable-pump-operating-ranges
               (system-data (pipe-diameter ?D))
               (operation-parameters          (max-discharge-vel ?max-dis-vel)
```

```
                                    (max-suction-vel   ?max-suc-vel)
                                    (max-impeller-prph-speed ?max-imp-vel)
                                    (min-percent-QBEP ?min-Qbep)
                                    (max-percent-QBEP ?max-Qbep))
                    (pump-BEP-char (pump-number ?n) (RPM ?rpm) (Qbep ?Qbep))
                    ?pump-curve <- (pump-curve (pump-number ?n) (flow-rate ?Q) (RPM ?rpm) (eff ?eff) (acceptability
~no))
                    =>
            (bind ?vm            (* 4 ?Q (/ 1 (pi) ?D ?D)))
            (bind ?vsm           (vsm-calc ?D))
            (bind ?imp-vel       (* ?rpm (pi) (/ 1 180) (/ 0.8 2.0)))
            (if (or     (> ?vm ?max-dis-vel)        (> ?vm ?max-suc-vel)
                        (> ?imp-vel ?max-imp-vel)
                        (< (/ ?Q ?Qbep) (/ ?min-Qbep 100))
                        (> (/ ?Q ?Qbep) (/ ?max-Qbep 100))
                        (< ?vm ?vsm))
            then
                        (modify ?pump-curve (acceptability no))
            )
)


defrule system-calc
            (pump-curve        (pump-number ?n) (flow-rate ?Q) (head ?pump-head)(RPM ?RPM)(acceptability
yes))
            (system-data       (elevation-difference ?z1) (digging-depth ?z2) (pipe-length ?L) (pipe-diameter
?D)
                               (suction-length ?ls)(equivalent-length ?Leq))
            (material-char     (d50 ?d50) (d85 ?d85) (Sm ?Sm))
            =>
            (bind ?cv          (/ (- ?Sm ?*S-fluid*) (- ?*S-solid* ?*S-fluid*)))
            (bind ?vm          (/ (* 4 ?Q) (* (pi) ?D ?D)))
            (bind ?iw          (iw-calc ?vm ?D))
            (bind ?im-iw                 (im-iw-calc ?vm ?D ?d50 ?d85 ?cv))
            (bind ?im          (+ ?im-iw ?iw))
            (if (neq ?cv 0.0) then       (bind ?SEC (/ (* 5.33 ?im) (* ?*S-solid* ?cv))))
            (bind ?velocity-head          (/ (** ?vm 2) (* 2 ?*gravity*)))
            (bind ?suction-head (- (+ (/ (* ?im (+ ?ls ?Leq)) ?Sm) ?velocity-head ?z2)    (/ ?z2 ?Sm)))
            (bind ?system-head (- (+ (/ (* ?im (+ ?L  ?Leq)) ?Sm) ?velocity-head ?z2 ?z1) (/ ?z2 ?Sm)))
            (bind ?head-difference        (- ?system-head ?pump-head))
            (bind ?avail-suc-head         (- (/ (- ?*Hbar* ?*Hvap*) ?Sm) ?suction-head))
            (assert (system-curve        (flow-rate ?Q) (head ?system-head)(head-difference ?head-difference)
                                         (NPSHA ?avail-suc-head)(pump-number ?n)(RPM ?RPM)(Sm ?Sm)))
;           (printout system-curve-data ?n "," ?Q "," ?system-head "," ?Sm "," ?RPM crlf)
)



;(defrule MATCH-INPUT-PROCESSED-FACTS::interpolate-pump-performance
(defrule interpolate-pump-performance

            (system-curve (pump-number ?n) (Sm ?Sm)(flow-rate ?Q1) (head ?h1) (head-difference ?dh1&:(>
?dh1 0))(RPM ?RPM) (NPSHA ?NPSHA1))
            (not (system-curve (pump-number ?n) (Sm ?Sm)(RPM ?RPM)(head-difference ?any-dh1&:(> ?any-
dh1 0)&:(< ?any-dh1 ?dh1))))
            (system-curve (pump-number ?n) (Sm ?Sm)(flow-rate ?Q2) (head ?h2) (head-difference ?dh2&:(<
?dh2 0))(RPM ?RPM)(NPSHA ?NPSHA2))
            (not (system-curve (pump-number ?n) (Sm ?Sm)(RPM ?RPM)(head-difference ?any-dh2&:(< ?any-
dh2 0)&:(> ?any-dh2 ?dh2))))
            (pump-curve (pump-number ?n) (flow-rate ?Q1) (RPM ?RPM)(NPSHR ?NPSHR1)(power ?PWR1)(eff
?eff1))
            (pump-curve (pump-number ?n) (flow-rate ?Q2) (RPM ?RPM)(NPSHR ?NPSHR2)(power ?PWR2)(eff
?eff2))
            (system-data       (pipe-length ?L) (suction-length ?ls))
            =>
            (bind ?cv          (/ (- ?Sm ?*S-fluid*) (- ?*S-solid* ?*S-fluid*)))
            (bind ?Q           (- ?Q2 (/ (* ?dh2     (- ?Q2 ?Q1)) (- ?dh2 ?dh1))))
            (bind ?h           (- ?h2 (/ (* (- ?Q2 ?Q) (- ?h2 ?h1)) (- ?Q2 ?Q1))))
            (bind ?NPSHR               (- ?NPSHR2 (/ (* (- ?Q2 ?Q) (- ?NPSHR2 ?NPSHR1)) (- ?Q2 ?Q1))))
            (bind ?NPSHA               (- ?NPSHA2 (/ (* (- ?Q2 ?Q) (- ?NPSHA2 ?NPSHA1)) (- ?Q2 ?Q1))))
            (bind ?eff         (- ?eff2 (/ (* (- ?Q2 ?Q) (- ?eff2 ?eff1)) (- ?Q2 ?Q1))))
```

```
                     (bind ?PWR                    (- ?PWR2 (/ (* (- ?Q2 ?Q) (- ?PWR2 ?PWR1)) (- ?Q2 ?Q1))))
                     (bind ?PWR                    (* ?PWR ?Sm))
                     (bind ?SEC 999)
                     (if (neq ?cv 0.0) then        (bind ?SEC (/ (* 5.33 ?h ?Sm) (* ?*S-solid* ?cv (+ ?L ?ls)))))
                     (assert          (pump-performance (pump-number ?n) (Sm ?Sm)(flow-rate ?Q) (head ?h)
(power ?PWR)
                                                   (NPSHR ?NPSHR) (NPSHA ?NPSHA)(RPM ?RPM)(eff ?eff) (SEC
?SEC)(acceptability yes))
                     )
                     (printout pump-performance-data ?n "," ?Sm "," ?Q "," ?h "," ?PWR "," ?RPM "," ?NPSHA ","
?NPSHR "," ?SEC crlf)

;                    (printout t ?n "," ?Sm "," ?Q "," ?h "," ?PWR "," ?RPM "," ?NPSHA "," ?NPSHR "," ?SEC crlf)


)

(defrule cavitation-check
                     ?pump-performance <- (pump-performance        (flow-rate ?Q) (pump-number ?n)(head ?h)(Sm
?Sm)(RPM ?RPM)(power ?PWR)(acceptability yes)
                                                   (NPSHR ?req-suc-head)(SEC ?SEC&:(numberp
?SEC))
                                                   (NPSHA ?avail-suc-head&:(< ?avail-suc-head
?req-suc-head)))
                     (system-data          (elevation-difference ?z1) (digging-depth ?z2) (pipe-length ?L) (pipe-
diameter ?D)
                                                   (suction-length ?ls)(equivalent-length ?Leq))
                     (material-char        (d50 ?d50) (d85 ?d85) (Sm ?Sm))
                     =>
                     (format cavitation-summary "Running the pump at %4d RPM with a Sm of %2.3f on pump %3d will
induce cavitation %n" ?RPM ?Sm ?n)
                     (modify ?pump-performance (acceptability no))
)


(defrule print-pump-performance
                     (pump-performance            (flow-rate ?Q) (pump-number ?n)(head ?h)(Sm ?Sm)(RPM
?RPM)(power ?PWR)(acceptability yes)
                                                   (NPSHR ?req-suc-head)(SEC ?SEC&:(numberp ?SEC)) (NPSHA
?avail-suc-head&:(>= ?avail-suc-head ?req-suc-head)))
                     (system-data          (elevation-difference ?z1) (digging-depth ?z2) (pipe-length ?L) (pipe-
diameter ?D)
                                                   (suction-length ?ls)(equivalent-length ?Leq))
                     (material-char        (d50 ?d50) (d85 ?d85) (Sm ?Sm))
                     =>
                     (printout pump-performance-summary "With a d50,d85,max-Sm of :" ?d50 "," ?d85 "," ?Sm crlf)
                     (printout pump-performance-summary "P/L len: " ?L crlf)
                     (printout pump-performance-summary "P/L diam: " ?D crlf)
                     (printout pump-performance-summary "P/L dig-depth: " ?z2 crlf)
                     (printout pump-performance-summary "P/L lift: " ?z1 crlf)
                     (printout pump-performance-summary "P/L suc-len: " ?ls crlf)
                     (printout pump-performance-summary "P/L minor loss: " ?Leq crlf)
                     (format pump-performance-summary "For pump number: %3d at %4d RPM and a SpG of: %4.3f %n"
?n ?RPM ?Sm)
                     (format pump-performance-summary "The pump will yield a performance of %4.2f cms and %4.1f m
%n" ?Q ?h)
                     (format pump-performance-summary "This amounts to %4.2f gpm and %4.1f ft. %n" (* 15850.3 ?Q)
(/ ?h 0.3048))
                     (format pump-performance-summary "%6.1f HP is required from this pump with a SEC of %1.3f HP-
Hr/T-Mi." ?PWR ?SEC)
                     (format pump-performance-summary "%n %n")
)


;(defrule PROCESS-OUTPUT::min-SEC-output
(defrule min-SEC-output
                     (pump-performance            (pump-number ?n)(Sm ?Sm)(RPM ?RPM) (SEC ?min-SEC)(eff ?eff)
                                                   (power ?power))
                     (not (pump-performance        (SEC ?any-SEC&:(< ?any-SEC ?min-SEC))))
                     =>
```

```
                    (assert (min-SEC-performance-point      (pump-number ?n) (Sm ?Sm)(RPM ?RPM) (SEC ?min-
SEC)(eff ?eff)
                                                                       (power ?power))
                    )
)


(defrule acceptable-pump-rpm-Sm
                    (pump-performance          (flow-rate ?Q) (pump-number ?n)(head ?h)(Sm ?Sm)(RPM ?RPM)(eff
?eff)(power ?PWR)(acceptability yes)
                                               (NPSHR ?req-suc-head)(SEC ?SEC&:(numberp ?SEC)) (NPSHA
?avail-suc-head&:(>= ?avail-suc-head ?req-suc-head)))

                    =>
                    (format other-SEC-summary "pump %3d can also be run at %4d RPM at Sm of %1.3f %n" ?n ?RPM
?Sm)
)

;(set-current-module MAIN)(format min-SEC-summary "%1.3f %3d %4d %4.3f %1.4f %n" ?Sm ?n ?RPM ?SEC ?eff)
```